Models for the infrared emission from starburst galaxies

Andreas Efstathiou[1], Ralf Siebenmorgen[2], and Michael Rowan-Robinson[1]

[1] Imperial College, Blackett Lab, Prince Consort Rd, London SW7 2BW
[2] ISO Science Operations Centre, Astrophysics Division of ESA, Villafranca del Castillo, P.O.Box 50727, E-28080 Madrid

Abstract. We present illustrative models for the UV to millimeter emission of starburst galaxies which are treated as an ensemble of optically thick giant molecular clouds (GMCs) centrally illuminated by recently formed stars. The models follow the evolution of the GMCs due to the ionization-induced expansion of the HII regions and the evolution of the stellar population within the GMC according to the Bruzual & Charlot stellar population synthesis models. The effect of transiently heated dust grains/PAHs to the radiative transfer, as well as multiple scattering, is taken into account.

The expansion of the HII regions and the formation of a narrow neutral shell naturally explains why the emission from PAHs dominates over that from hot dust in the near to mid-IR, an emerging characteristic of the infrared spectra of starburst galaxies.

The models allow us to relate the observed properties of a galaxy to its age and star formation history. We find that exponentially decaying $10^7 - 10^8$ yrs old bursts can explain the IRAS colours of starburst galaxies. The models are also shown to account satisfactorily for the multiwavelength data on the prototypical starburst galaxy M82 and NGC6090, a starburst galaxy recently observed by ISO. In M82 we find evidence for two bursts separated by 10^7yrs. In NGC6090 we find that at least part of the far-IR excess may be due to the age of the burst (6.4×10^7yrs).

1 Introduction

As is well known a large fraction of the power emitted by galaxies (ranging from about 30% in normal galaxies to almost 100% in actively star forming galaxies or starbursts) lies in the infrared part of the spectrum as a result of reprocessing of starlight by dust. Extensive infrared observations of galaxies are therefore necessary in order to describe fully their energy output. With the advent of the Infrared Space Observatory (ISO) the spectra of a number of galaxies in the local Universe have been observed with unprecedented detail in the infrared. They invariably display a variety of absorption/emission features due to dust/molecules. It is clear that radiative transfer calculations in dusty media will be useful for the interpretation of these observations and a development of a better understanding of the origin of the infrared luminosity of galaxies.

Radiative transfer models for the infrared emission of starburst galaxies have been presented before by [1], [2], and [3]. These models used state of the art codes for calculating the transfer of radiation in dusty media and incorporated a model for the composition and size distribution of grains in the interstellar medium. The basic assumption of previous starburst models is that a starburst is made up of an ensemble of compact HII regions similar to those found in our galaxy.

All of the above models assume that the cloud ensemble in the starburst consists of a number of identical systems. In this paper we present illustrative models for the evolution of giant molecular clouds (GMCs) induced by massive star formation at their centers and calculate their infrared spectra. In the radiative transfer code we use, the effect of transiently heated particles/PAHs as well as classical grains is included. We also follow the evolution of the stellar populations with the models of [4]. This approach allows us to relate the observed properties of a starburst to its age and its star formation history. We illustrate these models by comparison with the IRAS colours of starburst galaxies as a class and with the multiwavelength data on M82 and NGC6090.

A more extensive discussion of the models presented in this paper can be found in [5].

2 A new starburst model

The basic assumption of our model for a starburst galaxy is that star formation takes place primarily within optically thick molecular clouds. This is supported by an array of observational studies (e.g. [6]) which show that molecular clouds are associated with young stars.

The mass of molecular clouds in our Galaxy ranges between $10^2 - 10^7 M_\odot$ with a mass distribution approximately following $M^{-1.5 \pm 0.1}$ ([7], [8]). It follows that about 70% of molecular mass is associated with GMCs more massive than $10^6 M_\odot$. If the mass distribution in a starburst follows a similar form as the Galactic one, and GMCs are at least as likely to be the sites of massive stars as the less massive molecular clouds, then we would expect the bulk of the luminosity of the starburst to arise from GMCs with a fairly narrow range of mass. In fact low-mass molecular clouds, like the nearby Taurus and Ophiuchus clouds, are known to form predominantly low-mass stars.

An indirect argument that massive star formation in galaxies takes place in GMCs with roughly a power-law mass distribution comes from HST observations of starburst galaxies ([9], [10]) which reveal a population of super star clusters following a luminosity function of a power-law form $\phi(L) \propto L^{-2}$. A similar slope is found for systems of young clusters in other galaxies (e.g. [11]). This luminosity function is quite unlike that of globular clusters although it has been suggested that it could evolve into one ([10]). In our model these star clusters represent the evolved counterparts of star clusters forming within GMCs, with the mass spectrum given above, after they have dispersed their nascent molecular clouds.

In previous studies we assumed that a starburst is an ensemble of identical star forming complexes, which we approximate as spherical. Here we refine this model by considering the fact that, given the starburst takes place over a finite period of time, the star-forming complexes that constitute it are bound to be at different evolutionary stages. We therefore use a simple evolutionary model for HII regions to construct a family of models that predict the infrared spectrum of HII regions as a function of their age. The defining characteristic of this model is that the HII regions formed by the ionizing stellar radiation compress the neutral gas and dust in the GMC to a narrow shell. The family of evolving HII region models will then form the basis of our starburst models under our assumption that the latter are an ensemble of giant HII regions at different evolutionary stages. For more details about the assumed evolutionary scheme the reader is referred to [5].

In order to get a first impression of the characteristics of our models we have in this paper confined our attention to the spherically symmetric case. Clearly, highly non-spherical geometries can arise especially at the latter stages of the evolution and we plan to explore these situations in future studies. The model we have assumed for the absorption/emission properties of the dust is an extension of the 'classical' grain model (e.g. [12] and references therein) to take into account the effects of small grains and molecules. The model is described in detail in [13] where it has been shown to account satisfactorily for the emitted spectra of dust in a number of environments (solar neighbourhood, planetary nebulae, star-forming regions).

The method of solution of the radiative transfer problem in dusty media is that used by [14] and [15]. The emission of the transiently heated particles is calculated according to the method of [13]. Proper treatment of the photodestruction of the PAHs and the sublimation of the large grains, at the inner part of the cloud, is taken into account.

3 Evolving HII region models

There are basically three free parameters in our model (the GMC total mass M_{GMC}, the efficiency of conversion of gas to stars η, and the initial GMC optical depth τ_V) which we fix by relating to observational constraints where available.

In Figure 1 we plot the spectral energy distributions of a GMC with assumed parameters $M_{GMC} = 10^7 M_\odot, \eta = 0.25$, and $\tau_V = 100$.

The SEDs of the GMCs vary significantly with age. In the early stages of the cloud's evolution its SED is predicted to be warmer and show little signs of PAH emission. This is partly because the stellar population is younger and the radiation field stronger. The main contributing factor though is that there is more hot dust inside the Stromgren sphere than at later times. The

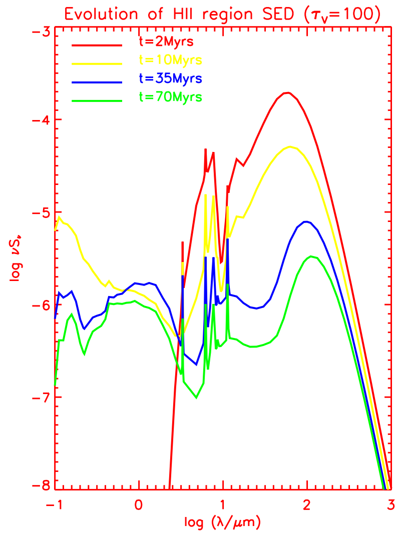

Fig. 1. Spectral energy distributions (right), of the GMCs at four representative ages of the HII region phase. The νS_ν scale is arbitrary but constatnt for all models

weakness of the PAH features is partly due to the stronger near to mid-IR continuum emission from large grains and to the higher degree of photodestruction because of the stronger and harsher radiation field.

By 10Myrs the mid-IR spectrum is dominated by the PAHs features and quasi-continuum and shows the characteristic shape that is observed in the spectra of starburst galaxies ([16], [17]). At $t > 20Myrs$ the peak of the SEDs of the shells shifts to longer wavelengths and become remarkably similar to those of the diffuse medium and cirrus clouds.

4 Evolving starburst models

To synthesize the spectral energy distribution from a burst of star formation from those of individual GMCs, let us assume that at time t after the onset of the starburst the star formation rate (or in our case the number of GMCs forming stars instantaneously with efficiency η) is $\dot{M}_*(t)$. If we further assume that the ensemble of clouds is optically thin, i.e. they don't shadow each other, then the flux from the burst is given by

$$F_\nu(t) = \int_0^t \dot{M}_*(t')S_\nu(t-t')dt' \tag{1}$$

where $S_\nu(t-t')$ is the flux from a GMC $t-t'$ years after the onset of star formation at its centre.

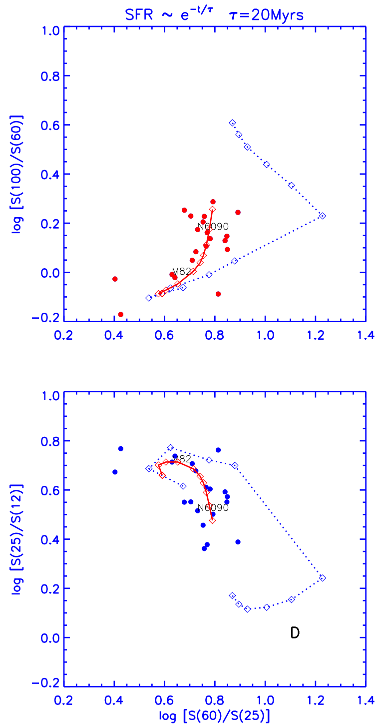

Fig. 2. IRAS colour-colour diagrams of starburst galaxies from the sample of [1] with models superimposed. The dotted line shows the colours of the sequence of GMCs. The ages indicated by open squares are (clockwise on the 25/12 versus 60/25 colour plot) 0, 1.7, 6.6, 10, 17, 26, 32, 37, 45, 57 and 72Myrs. The solid line shows the colours of a $\tau = 20Myrs$ starburst at the same ages. The symbol D denotes the position of the 'Disc' component of [1]

A useful parameterization for the star formation rate in a starburst which has been extensively used (e.g. [18], [17]) is that of exponential decay, $\dot{M}_*(t') \sim e^{-t/\tau}$, where τ is some time constant.

In Figure 2 we plot the IRAS colours of the starburst galaxies in the sample of [1] (selected to have good quality fluxes in all four IRAS bands) and indicate the position of their disc component (D). Also indicated in Figure 2 are the positions of M82 and NGC6090 on the colour-colour diagrams. Disc galaxies cover the part of the colour-colour diagram between the starbursts and D, although there is some overlap with the starburst galaxies.

If we consider first the predicted colours of the sequence of GMCs (dotted line), we see that they span the entire range of observed galaxy colours. This suggests that a weighted sum of emission from such a family of GMCs (which is what equation (12) essentially is) may explain the observed galaxy colours. To test this we have computed the colours of a galaxy that experienced an

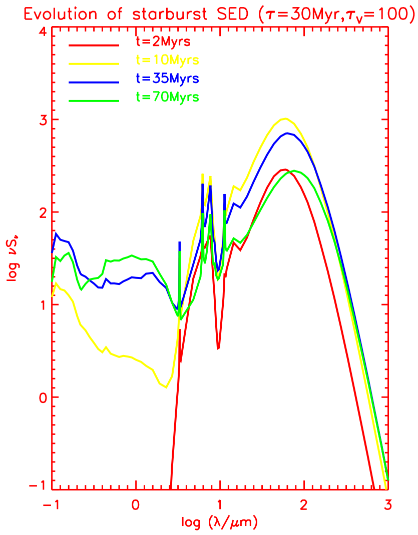

Fig. 3. Spectral energy distributions of a $\tau = 30Myrs$ starburst at different ages. The assumed GMC parameters are $M_{GMC} = 10^7 M_\odot, \eta = 0.25, \tau_V = 100$. The vertical scale is arbitrary but constant for the four models. Note the bolometric luminosity of the starburst peaks at about 10-20Myrs.

exponentially decaying burst with τ = 20Myrs (solid line). The predicted colours in the age range 0-72Myrs nicely match the spread in the colours of starburst galaxies. Furthermore, they predict a correlation of the 100/60 ratio, and an anticorrelation of the 25/12 one, with age. The predicted mean age of starburst galaxies ($\sim$ 50Myrs) agrees remarkably well with other estimates from Brγ equivalent widths and CO indices ([19]) as well as ISO spectroscopy ([17]). The predicted colours are not very sensitive on the assumed value of τ. The colours for the constant star formation case, a scenario more appropriate for disc galaxies, also lie on the same track but are packed towards the M82 end. This may have significant implications for the origin of the far-IR luminosity of disc galaxies. The conclusion from this analysis is therefore that the age of the burst can account for some of the variation in IRAS galaxy colours attributed by RRC to mixing with a cirrus component.

In Figure 3 we give the SEDs of the starburst discussed above (τ = 30Myrs) for some representative ages. A number of features are worth highlighting: (1) there is a general tendency for the peak of the SED to shift to longer wavelengths with age. (2) The PAH features get stronger with age. (3) the 9.7μm silicate feature gets shallower with age. (4) while the optical/UV light of the youngest bursts is almost completely obscured, the oldest starbursts are predicted to emit significantly in the optical/UV. This illustrates the extent to which old diffuse (and therefore optically thin) GMCs dominate the emission of old bursts.

5 Models for the M82 and NGC6090 starbursts

M82 being the nearest example of a starburst (D=3.25Mpc [20]) has received a lot of attention both observationally and theoretically. Our model fit, shown in Figure 4, assumes that M82 experienced two bursts of star formation. The first one occured 26.5Myrs ago and had a very steep exponential decay ($\tau = 2Myrs$). This burst is now responsible for most of the K band light and about half of the far-IR and submillimeter emission. The second burst occured 16.5Myrs ago and decayed more slowly ($\tau = 6Myrs$). The GMCs in both bursts are assumed to leak 20% of their starlight after 10Myrs which subsequently suffers a visual extinction of 1.5 magnitudes. The two bursts are predicted to contribute roughly equal amounts of UV flux.

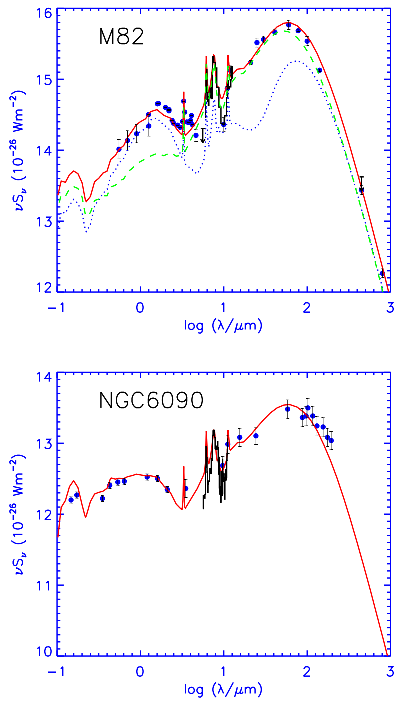

Fig. 4. Fits to the SEDs of M82 (top) and NGC6090 (botttom) with the starburst model. See test for model parameters

[18] presented ISO spectrophotometry and extensive multi-wavelength photometry for NGC6090. This galaxy is about 10 times more luminous than M82 and its optical image shows a disturbed morphology and signs of a recent interaction. The IRAS colours of NGC6090 show evidence for cold dust. It is therefore not surprising that the emission from an M82 type starburst has

to be supplemented by colder dust to fit the data for $\lambda > 120\mu m$ ([18]). We find that a good fit can be obtained with $t = 64$Myrs, $\tau = 50$Myrs.

6 Conclusions

We have presented models of the infrared emission of starburst galaxies which are treated as an ensemble of GMCs at different evolutionary stages. While useful constraints on the star formation history and stellar populations of galaxies can be obtained from this model, it will be of much interest to explore in the future the effect of deviations from spherical symmetry especially at the later stages of GMC evolution. Hydrodynamical simulations of the evolution of star-forming molecular clouds which take into account the effects of ionization, stellar winds and multi-supernova explosions in dense environments should also take high priority. Only then will we be able to take full advantage of the data ISO, SCUBA, WIRE, SIRTF, NGST, VLT, FIRST, PLANCK, SOFIA, ALMA etc. are expected to yield over the next decade or so.

References

1. Rowan-Robinson, M., Crawford, J., 1989, MN 238, 523.
2. Rowan-Robinson, M., Efstathiou, A., 1993, MN 263, 675.
3. Krügel, E., Siebenmorgen, R., 1994, AA, 282, 407.
4. Bruzual, A & Charlot, S., GISSEL user guide.
5. Efstathiou, A., Rowan-Robinson, M., Siebenmorgen, R., 2000, MNRAS, astro-ph/9912252
6. Elmegreen, B.G., 1985, in Protostar and Planets II, p.33-58.
7. Dame, , T.M., Elmegreen, B.G., Cohen, R.S., & Thaddeus, P., ApJ, 305, 892.
8. Solomon, P.M., Rivolo, A.R., Barrett, J., & Yahil, A., 1987, ApJ, 322, 101.
9. O'Connell, R.W., Gallagher III, J.S., Hunter, D.A., Colley, W.N., 1995, ApJ, 446, L1.
10. Meurer, G.R., Heckman, T.M., Leitherer, C., Kinney, A., Robert, C., Garnett, D.R., 1995, AJ, 110, 2665.
11. Whitmore, B.C., & Schweizer, F., 1995, AJ, 109, 960.
12. Mathis, J.S., 1990, ARAA, 28, 37.
13. Siebenmorgen, R., Krügel, E., 1992, AA, 259, 614.
14. Efstathiou, A., Rowan-Robinson, M., 1990, MN, 245, 275.
15. Efstathiou, A., Rowan-Robinson, M., 1995, MN, 273, 649.
16. Acosta-Pulido, J.A., *et al.*, 1996, AA, 315, 121.
17. Genzel, R., et al 1998, ApJ, 498, 579.
18. Rieke, G.H., Lebofsky, M.J., Thompson, R.I., Low, F.J., Tokunaga, A.T., 1980, ApJ, 238, 24.
19. Goldader, J.D., Joseph, R.D., Doyon, R., Sanders, D.B., 1997, ApJ, 474, 104.
20. Tammann, G.A., & Sandage, A., 1968, ApJ, 151, 825.